SAND2012-7271C

# Wave Energy Development Roadmap: Design to Commercialization

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***Abstract*— In order to promote and support development of the wave energy industry, Sandia National Laboratories (SNL) has developed a Wave Energy Development Roadmap. The Wave Energy Development Roadmap outlines the pathway from initial design to commercialization for Wave Energy Converter (WEC) technologies. Commercialization of a wave energy technology is embodied in the deployment of an array of WEC's, a WEC Farm. The development process is related to the commonly used metric of Technology Readiness Levels (TRLs). The roadmap incorporates modeling and experimental expectations at corresponding TRLs which provide a guide for the industry to pursue successful design optimizations, prototype deployments, and utility scale commercialization. The roadmap serves the additional purpose of pinpointing research gaps in the development process.**

***Index Terms*—Wave Energy, Roadmap, Technology Readiness Levels. Numerical Modeling, Experimentation**

## I. INTRODUCTION

Wave energy is a renewable energy source with high energy density and great potential. Along the coastal territories of the United States alone is 300 GW of potential wave resource [1]. In order to promote and support the wave energy industry, Sandia National Laboratories (SNL) created a Wave Energy Development Roadmap that proposes a development pathway for Wave Energy Converters (WECs). Each stage is linked to a Technology Readiness Level (TRL) in order to highlight the stages of a design's maturity.

The roadmap provides a suggested pathway from initial design concept to commercialization of a wave energy technology by highlighting the numerical modeling and experimental testing that accompany the development process. Both numerical modeling and experimental testing can be completed with distinct degrees of accuracy and fidelity. These distinct levels correspond to the TRLs. Thus, as the design progresses towards deployment the level of numerical modeling and testing also increases in the accuracy with which it represents the device.

Numerical modeling offers a relatively fast and inexpensive approach to evaluate device design optimization and power performance. Experimentation provides insight into the device design that cannot be obtained numerically. Complementary experiments can be used to deepen capabilities of the WEC developer by offering pathways for refinement of the numerical models. The SNL Wave Energy Development Roadmap links numerical modeling and experimental testing with similar precision levels so that these feedback pathways become clear.

The SNL developed WEC roadmap is intended for use by developers, investors, and researchers. Early stage developers can use it to guide their understanding in the development process. The roadmap further helps identify personnel capabilities that will be required to successfully design a device. In addition, an investor could use the roadmap to evaluate the TRL level at which a company currently resides. The roadmap will help investors to generate questions that can lead to more accurate assessments of a companies' progression. Furthermore, the roadmap can be used by researchers to identify locations where the industry could benefit from more research and development.

This paper will detail the TRL guidelines and will then develop a roadmap describing the advancement of wave energy technologies.

## II. TECHNOLOGY READINESS LEVELS

Technology Readiness Levels are used to classify new or unproven technologies by identifying elements and processes of technology development required to reach proven maturity levels and ensure project success [2]. Technology readiness assessments define a technology's TRL and are used to determine when a new technology is "Operationally Ready." The DoE Water Power TRLs were modified from the National Aeronautics and Space Administration (NASA) and Department of Defense (DoD) technology assessment model to better suit marine and hydrokinetic (MHK) devices [3]. The DoE Water Power TRL guidelines focus heavily on experimentation and prototype demonstration. To more fully capture the WEC technology development process, the TRL guidelines have been further refined in this paper to incorporate the numerical modeling that is complementary to the experimentation.

All development processes begin with a concept that arises from an exploration of the governing principles; this stage is embodied in TRL 1/2.

In TRL 3, research is initiated in the form of an elementary numerical model and concept exploration. The concept exploration occurs both numerically and experimentally.

Once a concept has been selected, the next phase of design in TRL 4 focuses on developing the basic component models that are necessary to progress towards advanced concept designs. A medium scale concept verification test is necessary to assess and refine the advanced concept design.

Specialized numerical models must then be developed to move the advanced concept into reality in TRL 5. These specialized models should be representative of full-scale concerns. In addition, small to medium scale testing with goals related to specialized conditions should occur.

TRL 6 is characterized by topics related to system integration concerns. Numerical modeling may require synthesis at this point where results from specialized models are integrated into a system package. In this stage, full-scale subassemblies may undergo testing in controlled conditions. Further, fully integrated technologies should be tested at a relevant scale (1:10 scale or larger) to reflect the challenges and realities of a full-scale system.

Testing in TRL 6 will have successfully demonstrated a technology's readiness to move to open water. TRL 7 is characterized by a short duration full-scale prototype deployment in open water. This deployment will integrate all components at full-scale and should verify the expected operation.

TRL 8 is a long-term full-scale deployment of the technology in the open water. This deployment should exhibit all functionality of the technology. The technology should expect to encounter all operating conditions, as this stage should demonstrate readiness of the individual design for commercial deployment.

Actual commercial-scale technologies are designated TRL 9. The technology is in its final form, it is fully functional, and is operating consistent with expectation.

## III. ROADMAP OVERVIEW

In order for wave energy to become a commercially viable technology, most WECs will be deployed in arrays creating WEC Farms. Thus, the commercialization of a wave energy technology is embodied in the development of a WEC Farm. Hence true commercialization of a WEC technology requires both a single WEC development process and a WEC Farm development process. In this paper, the TRL guidelines presented previously are applied to both the WEC Modeling and Development Roadmap and the WEC Farm Modeling and Development Roadmap.

A roadmap detailing the progress of a single WEC is detailed in the WEC Modeling and Development Roadmap shown in Appendix A. The advancement of the single design is catered to creating a robust and accurate understanding of the device in a representative deployment climate. This roadmap aligns strongly with the TRL definitions detailed previously. The individual WEC Modeling and Development Roadmap concludes at TRL 8. It is possible to have a business plan that does not revolve around utility scale deployments, thus TRL 8 incorporates this type of business plan for distributed power generation.

A roadmap catered to the unique issues to be encountered in developing a WEC Farm has been created in concert with a roadmap addressing an individual WEC. Development of a WEC Farm should not occur until there is a sufficient level of confidence in the single WEC device design. Thus the WEC Farm Modeling and Development Roadmap, Appendix B, branches off from a relatively mature single WEC, corresponding to WEC TRL 5. It is expected that development of a single WEC will still be occurring during the initial stages of WEC Farm development. Additionally, because the WEC Farm development is based on a mature WEC design, the TRL definitions are applied without incorporating as much demonstration and testing.

## IV. WEC MODELING AND DEVELOPMENT ROADMAP

In this section, a WEC device development roadmap will be introduced and described. The WEC Modeling and Development Roadmap, Appendix A, presents a suggested pathway for a single WEC device development that is coupled to the TRLs described above. This pathway begins with basic design concepts and builds the design through full-scale deployment. Feedback and iteration will be necessary between many of the development stages, but only the required links are specified in the roadmap itself.

### *A. WEC TRL 1/2 Stages*

The first stage of development is to determine what type of WEC to pursue. There are a variety of WEC types and thus understanding the design limitations and constraints of each particular WEC type is important. Some design topics to consider include deployment depth, floating or submerged design, Power Take-Off (PTO) options, and anchor and mooring requirements. The type of WEC chosen will arise from an exploration of the design topics as well as themes relating to a full-scale design. These themes include: power performance, survivability, environmental concerns, and operations and maintenance. A strategy should be developed identifying how each of themes should be addressed. By developing a set of metrics that reflect the strategy and applying them to each WEC type, a choice that reflects the developers' values will be possible. Possible metrics include: power output, manufacturability, survivability, serviceability, stability, and environmental transparency.

Once a WEC type is narrowed down, the next stage is Generation of WEC Concept Designs. It is likely that these concept designs will be variations on the profile of a particular WEC type. If these concept designs are variations on the WEC type, then numerical and experimental testing will need to explore the design metrics identified above.

### *B. WEC TRL 3 Stages*

During the Initial WEC Modeling stage, a fundamental understanding of the basic mathematical relationships should be established allowing for comparison of the concept designs. Development of a linear frequency-domain model using hydrodynamic inputs from potential flow solvers such as

AQWA or WAMIT is recommended [4], [5]. This will facilitate understanding how things like size, wave direction, water depth, and wavelength affect the mechanical power performance of each of the concept designs. Elementary control strategies will be required to maximize the mechanical power performance of each concept.

These concept designs should be evaluated through Small Scale Experimental Wave Tank Testing (1:100-1:25). This experimentation should allow for qualitative assessment of concept designs in comparison to one another. Assessment parameters may include stability, mechanical power conversion, and mooring design. The testing environment does not have to represent expected operational conditions; regular waves, simplified profile designs, and simplified PTO's (if mechanical power conversion is a comparison parameter) are sufficient.

Lastly, the final stage of WEC TRL 3 is to pick a single concept design to pursue in the next TRL level.

### *C. WEC TRL 4 Stages*

WEC TRL 4 develops component models required to formulate an advanced concept design. These component models relate to the power performance, the physical structure, the method of localizing the structure, and the physical method of converting mechanical power to electrical power. Each of these models is interrelated and require distinct personnel, thus co-development is recommended and illustrated through branching of the roadmap levels. These component models are in their initial development phase, however, consideration of specialized models, to be developed in later TRLs, should begin for each model. The final phase of this TRL is verification of this advanced concept design in an experimental test.

The first stage of development in WEC TRL 4 is WEC Numerical Modeling. The goal of the numerical model is to create a platform capable of incorporating results from the other component models developed in this TRL in order to predict the mechanical power produced by the device. The numerical model should produce time domain results that can be compared directly with the experimental tests.

In attaining this goal, it may be necessary to complete the previously started linear frequency-domain model; however transitioning to a time-domain model is paramount. The time-domain numerical model should be capable of accounting for non-linearities due to the viscosity of water and physical design constraints. In addition, the time-domain model should incorporate results from the structural design, the mooring system design, the PTO design, as well as any control strategies to be pursued. This model can be created with the commercial code AQWA using its time-domain solver with a DLL calling on external forcing. Alternatively, this can be accomplished using hydrodynamic inputs from WAMIT and developing a time-domain wrap around in MATLAB/Simulink (or similar) using the Cummins' impulse response formulation [6–8].

During this stage, it should also be determined whether understanding the non-linearities of the Fluid-Structure-Interaction (FSI) between the wave and the WEC will be necessary. If deemed necessary, fully non-linear computational fluid dynamics (CFD) modeling should begin. CFD results are not necessary at this stage, but this capability takes a long time to develop. Additional guidance and recommended practice for WEC numerical modeling is available through SuperGen [9].

In the Structural Design and Modeling stage the concept is modeled in a 3-D CAD program. This model should incorporate a robust structural representation of the device that can yield realistic estimates of: mass, center of mass, and moments of inertia. Static structural load analysis should be performed using realistic wave loads. The goal is to ensure that the WEC design has both structural and hydrodynamic stability. The design should incorporate strategies to address deployment, recovery, and operation and maintenance.

Mooring Design and Modeling should occur simultaneously with the structural design and modeling. Selection of a mooring design is dependent upon many factors: shallow or deep water deployment, primary motion of the WEC (heave, pitch, etc.), seabed type, and desired watch circle [A]. Typically the extreme wave environment will drive the size of the system components, and hence it is used to design the mooring system. OrcaFlex is the industry standard for mooring system design and analysis [10]. However, ANSYS has recently integrated the Coupled Cable Dynamics package with AQWA, which may prove useful to developers already using AQWA's time-domain solver. Additional factors to consider in the mooring system design are: cost, ease of installation, translation to different deployment sites, and scalability for WEC Farm integration.

PTO Design and Modeling is the last component model developed in this TRL. The method of conversion to usable power must first be determined. Commonly used WEC PTO systems include: direct drive, hydraulic, mechanical, and various turbine configurations. Similar to the process for narrowing down the WEC concept designs to a single WEC design, each PTO system's design limitations and constraints should be understood before a particular PTO system is pursued. Specific themes to explore include: required maintenance, efficiency, power quality, and ability to execute the desired control strategy. A MATLAB/Simulink model of the selected PTO incorporating vendor supplied efficiency data should be generated. Consideration towards control strategies incorporating PTO capabilities to further increase power output in operational waves and survive extreme wave environments should begin.

The final stage of development in WEC TRL 4 is Medium Scale Experimental Wave Tank Testing (1: 25-1:10). The medium scale WEC should be subject to waves representative of a site's wave climate [11]. Response and stability at dominant wave periods should be thoroughly tested, accounting for bimodal spectra where applicable. Properties like the WEC's resonance periods, moments of inertia, center of gravity, and response amplitude operators should be experimentally determined. In order to accurately capture the WEC's dynamics, both a motion tracking system and an onboard accelerometer should be implemented. The test should incorporate a realistic representation of the operational characteristics of the mooring design. If the selected PTO is easily scalable, then it should be used in this experiment; otherwise a fully characterized representational PTO capable of implementing the control strategy should be used. Results from the medium scale experimental testing should be used to verify and refine the numerical models developed in previous stages of the TRL. An expected refinement relates to the magnitude of the viscous damping parameter. Guidance and recommended practice for WEC wave tank testing is available through SuperGen [13].

### *D. WEC TRL 5 Stages*

WEC TRL 5 develops and tests specialized models in order to progress the advanced concept in WEC TRL 4 towards a physically realizable design. Again the roadmap splits into multiple development branches, indicating parallel development and distinct personnel requirements.

The time-domain power performance model is further refined and updated in the Rigorous WEC Numerical Modeling stage. Direct coupling between the PTO, mooring, and power performance models should be pursued. Evolution of the numerical model in this stage will result in electrical power predictions. Results from the medium scale experimental test should be used to adjust the selected control strategy. Additionally, the control strategy should now be coupled to the PTO model such that all limitations and losses resulting from the PTO can be accounted for in the strategy. Additionally, if CFD models were deemed necessary, their development and refinement should be ongoing to account for fluid-structure non-linearities. WECs will likely be deployed in the most energetic climates making WEC survivability a vital issue. Wave Tank Survival Testing occurs in this TRL as it is a specialized experimental condition. Wave tank survival testing is essential because numerical models are limited in their ability to predict survival loads. The scale of survival testing will be limited by both the WEC's and the wave tank's dimensions, but should be performed at the largest scale possible (~1:50). Wave tank capabilities must be carefully scoped for this test since survival conditions push wave-maker capabilities to their threshold. This test should include a representative mooring system and PTO survival strategy. Definition of survival conditions should be based on a resource assessment.

Specialized Structural Modeling should occur for the the structural subsystem. Survival loads resulting from extreme wave events should be applied to the structure. This analysis, completed with finite element analysis codes, should result in industry accepted factors of safety for the structural design. Additionally, fatigue loads resulting from repeated motions at the mooring connection points and at any other connection points should have dedicated fatigue modeling completed.

Specialized Mooring Modeling should occur for the mooring system. However, because the mooring system was initially designed to withstand extreme wave events, only a fatigue study should be completed for this subsystem. The results of this study will be an important input into maintenance schedules.

Specialized PTO Modeling should also occur for the PTO system. This model will mainly focus around a reliability model in order to more accurately understand the maintenance schedules that will accompany the deployment of the WEC. The survival loads should also be used to ensure that the survival strategy for the PTO will be sufficient.

A WEC Telemetry Design should be developed in conjunction with the previously mentioned stages in WEC TRL 5. This specialized design should address sensor selection, data acquisition, controller specification, and integration into a human machine interface. Details to consider when designing the WEC telemetry are: what and how the data should be collected, how often it should be sampled, how it is stored, transmitted and processed, and finally, what it is used for. Once the telemetry is designed, it should be implemented whenever possible.

### *E. WEC TRL 6 Stages*

WEC TRL 6 explores system integration through large scale or full-scale testing and fabrication of full-scale components.

Large Scale Testing enables the first system integration of subsystems. It should occur in either a large wave tank or in a nursery site with scaled seas (1:10-1:3). The device should be sufficiently instrumented to monitor all areas of concern in order to mitigate risk at the next TRL. Large scale testing should be completed with a scaled PTO incorporating the WEC Telemetry Design. Testing at large scales will also overcome issues that arise at small scales with Reynolds versus Froude scaling. The motivation for large scale wave tank testing is to ensure that the WEC's components perform as expected in a controllable and repeatable environment before it is deployed in the open ocean. As such it is preferable to perform testing at this scale in a wave tank whenever possible.

Fabrication of a full-scale PTO integrating the WEC Telemetry Design should culminate in Full-Scale PTO Characterization. Characterization should occur in a test bed capable of simulating the expected loading conditions in both operational and extreme wave environments. The final control strategy should be implemented during this stage since it will directly influence the PTO's response. Full-scale PTO characterization should be used to further refine the PTO model ensuring that it accurately captures the PTO's response for all loading conditions.

### *A. WEC TRL 7 Stage*

Successful mitigation of risks in the earlier TRLs leads to this penultimate stage: Full-scale Prototype Demonstration without grid connection or application. A prototype of the device should be deployed in the open ocean with all subsystems for a limited duration. Full-scale subsystems include: mooring, characterized PTO, telemetry, and the structure itself. Due to the limited duration deployment, instrumentation capable of monitoring specific areas of concern highlighted in the large scale testing (e.g. mooring loads, a particular structural load, etc.) may be incorporated to more fully understand the device's operation in open waters. A method to monitor the incident wave climate is also recommended. The purpose of the prototype testing stage is to make sure that the overall WEC design is ready for full-scale deployment with grid connection, and that all systems function as expected.

### *B. WEC TRL 8 Stage*

The final stage in single device WEC Modeling and Development Roadmap is Full-scale Ocean Deployment with application or grid connection. This requires the developer to have completed all of the state and federal licensing and permitting process, which includes a FERC permit for grid connection, completion of an Environmental Assessment, and development of a continued monitoring plan [14]. At this stage, the full-scale WEC, including all subsystems, is deployed in the open ocean and is producing power. The developer should have a system implemented to transmit, process and use the data.

Single device development does not achieve TRL 9 because it refers to a commercial-scale technology, which only a WEC Farm can achieve. However, there are WEC technology business plans that focus on producing distributed power and hence, this final TRL encompasses this application.

## V. WEC Farm Modeling and Development Roadmap

In this section a WEC Farm Modeling and Development Roadmap will be introduced. This roadmap presents a framework for considering the issues unique to a WEC Farm development. Similar to single device development, this framework is coupled to the TRLs in order to highlight the maturity of the WEC Farm design. Since a mature WEC design is the foundation of a WEC Farm, WEC Farm development is not focused component development and testing to the same degree as for WEC device development. The development of a WEC Farm should not occur until there is a sufficient level of confidence in a WEC design, thus this WEC Farm Modeling and Development Roadmap does not begin until WEC TRL 5 has been achieved on the single device design. The WEC Farm Modeling and Development Roadmap is shown in Appendix B. Feedback and iteration will be necessary between many of the development stages, but only the required links are specified in the roadmap itself.

### *A. WEC Farm TRL 1/2/3 Stage*

The first stage in the development of WEC arrays is Generation of WEC Farm Designs through the exploration of the principles guiding WEC Farm design. The guiding principles originate from varied interests including: environmental, conversion performance, and infrastructure design. In this stage the WEC developer must identify the relevant principles guiding their WEC Farm design and develop a strategy based on these principles. A general exploration of these principles is given below.

Environmental concerns are often taken more seriously when considering WEC Farms since the impact of an array is expected to be much larger. The effect of the array on the wave energy downstream in the near- and far-field is extremely important. Ensuring that the array does not dramatically increase toxicity risks (from coatings or fluids in the device), acoustic noise levels, and EMF field generation to levels that could influence the habitat are important to scope. Another consideration revolves around placement of the array and migration patterns of species in the area.

Many stakeholders such as fishermen, recreational users, and regulators have a vested interest in assuring that the habitat and surrounding environment will not be deleteriously affected by the presence of a WEC array. As such, identifying key stakeholders at an expected deployment location and engaging them early in the process is advisable. In addition, identifying key environmental issues and developing plans to address those sensitivities is recommended early on.

Fundamentally, WECs should be placed in an array in order to reduce the Levelized Cost of Energy (LCOE). Thus, the performance of the array is extremely important. The performance of the array is a result of the individual WEC performance, but it is also a function of the array design. Thus considering the tradeoffs between very large WEC arrays and clusters of smaller arrays could be important to the performance [15]. WEC spacing within an array also affects apportioning of mooring components, which in turn could strongly affect LCOE. Another important consideration relates to the applicability of the WEC array design to multiple deployment locations.

Infrastructure at the array site will be an important design consideration. Determining the desired versus available capacity of electric cable and its associated cost should be a consideration in designing the WEC Farm. Additionally, storage and/or smoothing requirements for grid connection may need to be considered and scoped. Questions regarding the strengths and weaknesses of multiple, singular, or no substation should be developed and initial deliberation should commence.

Consideration of each of these key areas will results in a baseline array design. Basic properties should be unified into a WEC Farm design that addresses the above principles by defining: spacing, orientation, mooring, and electrical connections.

### *B. WEC Farm TRL 4 Stages*

WEC Farm TRL 4 focuses on developing component models and testing in a similar fashion to the single device TRL 4. These component models relate to the guiding principles explored in TRL 1/2/3, however they are now developed in numerical frameworks. The three numerical models to be developed are: WEC Farm Power Modeling, WEC Farm Environmental Modeling, and WEC Farm Hydrodynamic Modeling. Each of these models is capable of predicting results for the strategies adopted in designing the array.

The initial goal of the WEC Farm Power Model should be the development of a framework that is capable of evaluating multiple WECs in space. Initially, this framework requires knowledge of the incident wave at each WEC location and the response of each WEC to the unique waveform encountered. The response of each WEC should originate from the Rigorous WEC Numerical Modeling stage of single device development. The WEC Farm Power Model, developed in MATLAB/Simulink or similar, should be capable of estimating the power produced by the WEC Farm assuming non-interacting WECs. Anticipation of the optimized WEC Farm power model should result in a model design at this early stage that is capable of adding control strategies to be applied to the array.

WEC Farm Environmental Modeling should occur simultaneously with the WEC Farm's power modeling. This stage requires assessment of the environmental impacts of the WEC Farm on a large scale. Potential WEC Farm environmental impacts include sediment transport locally and at the shoreline, changes in the wave height and period, and bottom scour. The WEC Farm Environmental Model should be capable of quantifying these impacts by representing the WEC Farm in a large scale wave propagation model like SWAN [16]. The representation of the WEC Farm inside this model should attempt to depict the core capture characteristics of the device [17]. These results will be used to iteratively optimize the strategy and design of the WEC Farm. This is also the first step towards obtaining the appropriate licenses and permits for a WEC Farm and will facilitate discussions with regulators and stakeholders.

The WEC Farm Hydrodynamic Model should be developed to capture hydrodynamic interaction between WECs and/or their mooring. Hence, the scale of this model is considerably smaller than the Environmental Model. If the individual WECs can be assumed to be non-interacting due to spacing, then this stage may solely focus on developing mooring systems for the array in OrcaFlex. However, in general these models should be developed from wave-structure interaction codes, like AQWA and WAMIT capable of incorporating multiple interacting bodies. Similar anticipation regarding the incorporation of this model into a unified WEC Farm Model should result in a Hydrodynamic model at this early stage that will integrate easily with the WEC Farm Power Model.

With the completion of each of these component models, Scale Experimental Wave Tank Testing of the WEC Farm should begin to ensure early stage concept verification. The WEC Farm should be tested at the largest scale possible (in order to minimize vicious losses) in a directional wave basin. The scale WEC Farm experimental modeling should include a characterized PTO, a mooring system, and should be tested in a realistic wave climate based on the site's wave spectrum. Similar to single device experimentation, it is advisable to implement both an onboard accelerometer and motion tracking system to capture the WEC Farm's response. Before testing begins, it is important to think critically about the size, spacing, arrangement and array test setup in order to make sure all desired scenarios are covered. Results from this experimental testing should be used to verify and refine the numerical models developed in the previous stages.

### C. *WEC Farm TRL 5 Stages*

Once the array design has been verified through testing and component model results, numerical optimization strategies can now be developed as specified by the WEC Farm Power Optimization stage. In this stage, the WEC Farm's power output should be optimized by developing control strategies for the WEC Farm as opposed to individual WEC devices. The parameter space over which this optimization occurs is very important. The goal of the optimization (e.g. storage minimization, maximum power output, continuous power output, etc.) will determine the parameter space. The control strategy will require knowledge of the infrastructure with which the array will be deployed. Limitations originally identified in TRL 1/2/3 regarding the electrical connections (substations, cable capabilities, and grid requirements) must be quantified at this stage in order to effectively optimize the power produced from the array. These limitations will act as input to the control strategies. It is advisable that a few infrastructure configurations be tested.

### D. *WEC Farm TRL 6 Stages*

WEC Farm TRL 6 focuses on system integration of the component models, thus this stage develops a Combined WEC Farm Model. This model combines the WEC Farm Hydrodynamic Model and the WEC Farm Power Model. The combined model should account for array interactions, WEC hydrodynamic response, PTO and control, grid connection, and mooring. The Combined WEC Farm Model should be accurate enough to estimate both power and WEC response with reasonable robustness, so that the developer knows how their WEC Farm will respond to all possible wave conditions.

### E. *WEC Farm TRL 7/8 Stage*

Once the WEC Farm has been developed, tested, and modeled according to the proceeding TRL specifications, a Small WEC Farm Demonstration should be deployed in order to verify performance of the full-scale design. The deployment should capture the main aspects of the array design even though a limited number of devices are composing the array. It is expected that the devices will be grid connected at this stage in order to verify infrastructure operation, or at a minimum have grid emulation and power sinks. During this stage, the optimized control strategy should be verified with dedicated tests in the open ocean. These tests should also provide verification and refinement data for the combined WEC Farm Model. In addition, processes for monitoring environmental concerns should be implemented. This phase should be used to engage with the stakeholders and regulators as a phased demonstration of the full commercial deployment.

### F. *WEC Farm TRL 9 Stage*

The final stage in the WEC technology roadmap is Full-Scale WEC Farm Commercial Deployment with Grid Connection, corresponding to TRL 9. The full infrastructure should be available for delivery of power from each WEC to the grid. Sufficient telemetry should also be available so that WEC Farm data can be used by the developer as necessary. In order to accomplish full-scale commercialization, the developer will have had to complete the licensing and permitting process required at their deployment site. Typically this includes an Environmental Assessment, an established monitoring plan, and a FERC permit for grid connection [14].

## VI. Research Gaps and Conclusions

The single device and array WEC Development Roadmaps serve the additional purpose of identifying research gaps that need development. For single device development many of these areas are related to limited numerical modeling capabilities.

Early stage numerical modeling is typically limited to potential flow codes that have inviscid, irrotational flow with small amplitude motion assumptions. For WECs designed to move with the incident waves existing modeling capabilities are not sufficient, especially for extreme events such as storm waves, overtopping, and breaking waves. The alternative is CFD which is expensive to implement and computationally demanding, thus few developers pursue it.

Other single device development gaps lie in optimal control strategies for real seas, WEC telemetry design and large scale testing. Currently, a large scale testing facility suitable for this type of testing does not exist. However SNL has proposed to convert its Lake Facility into a large scale wave tank testing facility [18].

Additionally, all of the numerical modeling stages for WEC Farms need development. WEC Farm development is a topic developers are now beginning to pursue and tools dedicated to supporting industry need advancement. Another issue to consider when optimizing the control strategy is how the WEC Farm responds to extreme sea conditions.

In conclusion, the WEC single device and array development roadmap was developed by SNL to promote and support the maturing wave energy industry by proposing a development pathway for WECs. The roadmap links experimentation and numerical modeling stages with the commonly used metric of TRLs. The roadmap is intended for use by developers, investors, and researchers alike.

## Acknowledgment

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

This research was made possible by support from the Department of Energy's Energy Efficiency and Renewable Energy Office's Wind and Water Power Program.

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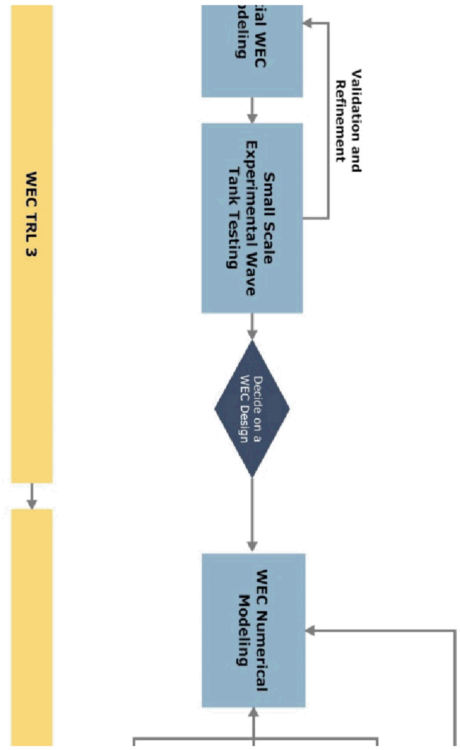
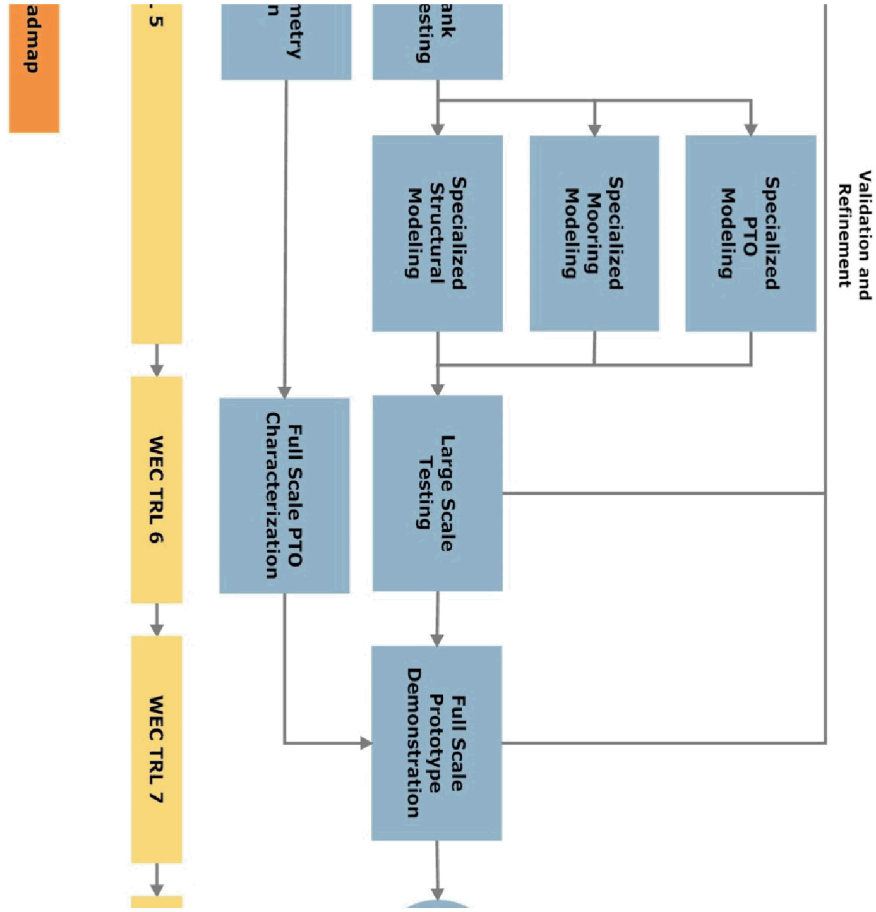
APPENDIX A: WEC DEVELOPMENT ROADMAP




WEC TRL 6
WEC TRL 7
Specialized Structural Modeling
Specialized Mooring Modeling
Specialized PTO Modeling
Validation and Refinement
Full Scale PTO Characterization
Large Scale Testing
Full Scale Prototype Demonstration

## APPENDIX B: WEC FARM DEVELOPMENT ROADMAP